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Carrier-envelope phase fluctuations of amplified femtosecond pulses: characterization with a simple spatial interference setup

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ABSTRACT We demonstrate a direct and versatile scheme to determine the carrier-envelope phase fluctuations of tunable ultrashort optical pulses. The spatial interferogram between the high frequency components and the parametrically amplified and frequency doubled low frequency components of an octave broad white light continuum is measured for every single pulse. It directly reveals the carrier-envelope phase fluctuations of the pump pulses from the regenerative amplifier, as well as of the white light and the tunable pulses generated from it.

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1 Introduction

Ongoing research on sources for ultrashort light pulses has led to pulse durations in the 5-fs regime [1–5]; such pulses consist of only a few optical cycles. Beyond pump probe spectroscopy with the highest time resolution [6, 7], they allow the investigation of phenomena that depend not only on the light intensity, but also on the electric field and its phase [8]. These experiments include the generation of high harmonics and attosecond pulses [9, 10], the design of optical synthesizers [11, 12], as well as coherent control schemes that use the interference between several optical excitation pathways [13, 14].

For such experiments it is necessary to know or control the phase of the carrier frequency with respect to the pulse envelope, i.e. the carrier-envelope phase (CEP). For Ti:sapphire oscillators a stabilization of the CEP drift frequency has been achieved by controlling the dispersion in the resonator [15–17] or the pump power [18]. Such oscillators are already very successfully used for high precision spectroscopy [15, 19–21]. However, their application to time resolved or high-intensity experiments suffers from some severe limitations. The energy per pulse is only in the order of several nJ, and it is most challenging to maintain control over the CEP through an amplification process [10]. The carrier-envelope phase of the oscillator pulses cannot be set to a fixed value, but is rather controlled via its oscillation frequency. The wavelength of the pulses is restricted to a spectral region around 800 nm. As was demonstrated recently, optical parametric down conversion of a white light continuum leads to near-infrared pulses with a stable carrier-envelope phase [22].

Since tunable pulses with a constant CEP are not easily available, a direct and versatile optical scheme for measuring the CEP of such pulses is highly desirable for performing CEP sensitive experiments with these sources. Beside setups using the light electron interaction [23, 24], spectral interferometry between different harmonics gives access to the carrier-envelope phase [25]. The CEP of 6-fs pulses from an optical parametric amplifier has been characterized using the unique properties of BBO at one specific angle [26]. For the wavelengths used, signal amplification and idler frequency doubling occurred simultaneously [26]. The CEP and the group delay fluctuations of intense pulses generated in a hollow fiber have also been measured by spectral interferometry [27].

In this communication we present a novel and simplified setup for accessing the carrier-envelope phase of a single pulse using spatial interference between different harmonics. It avoids the need for a spectrometer and for a collinear interferometric setup, as well as for broadband nonlinear elements. The scheme is very versatile with respect to the center wavelength and the intensity. We measure the CEP fluctuations of single white light pulses and generate tunable pulses with a measured CEP variation and with μJ energies.

2 Experimental

For our investigations we use the setup shown in Fig. 1. The pump system (CPA 2001, Clark MXR) provides 150-fs pulses at 775 nm with a repetition rate of 1 kHz and pulse-to-pulse intensity fluctuations of about 1% (rms). A portion on the order of 1 μJ is split off and focused into a 3-mm-thick sapphire plate to generate a single filament white light continuum. The pump energy for the continuum can be adjusted with a variable neutral density filter and an iris. The continuum is collimated by a fused silica lens. The spectrum extends from 440 to 1600 nm and thus covers more than one octave. About 50% of the white light is reflected by a broadband metallic beam splitter (BS in Fig. 1) and is guided to a delay stage. The other part

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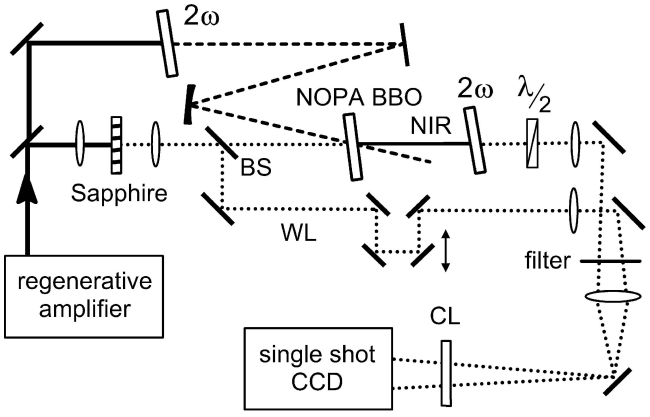

FIGURE 1 Experimental setup for the measurement of carrier-envelope phase fluctuations. *Solid beam*, 775 nm; *dotted beam*, white light continuum and second harmonic of amplified NIR part; *dashed beam*, 387-nm pump light for the NOPA stage; *filter*, interference filter and NIR blocking filter; *CL*, cylindrical lens

of the continuum is used to seed a noncollinear optical parametric amplifier stage (NOPA) with a 2-mm-thick BBO crystal [28, 29]. It is pumped by the second harmonic of the 775-nm pulses and aligned to boost the NIR frequency components around 1100 nm [30]. The generated NIR pulses are frequency doubled in a 2-mm-thick type-I BBO crystal without focusing (see Fig. 2 for spectra). The polarization of the second harmonic is rotated with an achromatic half-wave plate to be parallel to the polarization of the continuum.

The fundamental white light and the amplified and frequency doubled pulses are collimated by fused silica lenses so that they have comparable divergences. Both beams pass through an IR blocking filter and an interference filter ($\lambda_{\text{center}} = 550\,\text{nm}$, $\Delta\lambda = 10\,\text{nm}$) to block the Ti:sapphire fundamental and the amplified NIR components, and to restrict the white light spectrum to approximately that of the second harmonic (see Fig. 2). The beams are separated from each other by about 2 mm and are slightly diverging, and they pass a lens ($f = 500\,\text{mm}$) to interfere in the far field at a distance of about 4 m. While carefully adjusting the temporal overlap and watching the common spot by eye on a screen, a surprisingly obvious interference pattern appears at time zero.

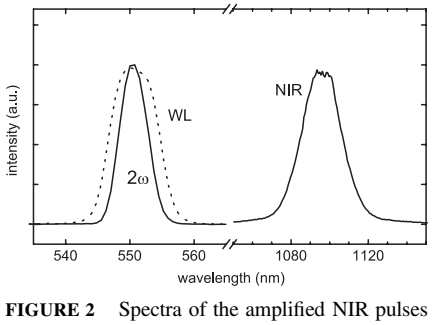

FIGURE 2 Spectra of the amplified NIR pulses and their second harmonic (*solid curves*) and the spectrum of the filtered white light continuum (*dotted curve*)

3 Results and discussion

The spatial position of the interference fringes is given by the relative phase between the two pulses. The relative phase depends on the difference in the optical path lengths, the group delay between the low and the high frequency components of the white light continuum, and on the CEP of the continuum. To understand the influence of the white light CEP on the interference pattern we have to consider the following nonlinear processes. Optical parametric amplification preserves the spectral phase of the white light, since the phase properties of the NOPA pulses are defined solely by the seed light and the amplification changes only the amplitude of the spectral components [22, 31]. Thus the amplified NIR pulses retain the phase properties of the white light. In the spectral domain, the CEP of short pulses corresponds to a frequency independent additive term to the spectral phase. This term doubles with frequency doubling according to the dependence of the nonlinear polarization on the electric field [11, 22]. Consequently, the CEP of the white light contributes twofold to the phase of the frequency doubled NIR pulses and only once to the phase of the visible part of the white light. Thus, the CEP adds linearly to the relative phase between the interfering pulses. This fact is widely used in numerous other experiments addressing the CEP, in which it is detected as a shift in the spectral interferogram or as a temporal beating [11, 15–22]. In the interferograms presented, the spatial position of the fringes directly gives the CEP with respect to a constant offset value.

Fluctuations of the optical path lengths would be mistaken for CEP fluctuations in the setup presented. To check for the mechanical and thermal stability of the setup, we removed the half-wave plate and blocked the pump beam of the NOPA amplification stage to suppress the amplification of the weak NIR part of the white light. The missing amplification drastically lowered the doubling efficiency. The two replicas of the white light generated by the beamsplitter BS interfered on the CCD camera through exactly the same beam path as in the CEP measurement. The observation of a highly stable visible interferogram (around 550 nm) demonstrates the stability of the setup on short and long time scales.

Fluctuations in the chirp of the white light could also lead to systematic errors. However, pulse trains of continua generated in sapphire or fibers were compressed to almost the Fourier limit [2–5], excluding variations of the chirp with time. If the CEP is determined by spectral interference, the differences in the chirp of the interfering pulses change the fringe spacing over the spectrum and make the evaluation difficult [26]. In our case the interfering pulses have a rather narrow spectrum and the spacing of the spatial interference fringes is independent of the chirp.

Pump intensity fluctuations in the NOPA crystal of 2% (rms) only induce CEP changes of less than 10^{-3} rad due to the nonlinear index of refraction. This can be estimated [18] from the energy and duration of the pump pulse and the spot size in the amplifier crystal of about 1 mm.

The observed interference pattern can be recorded by a beam analyzer camera with an integration time of about 30 ms. Similar to a preliminary experiment with two separate NOPAs [32], the position of the interference fringes

fluctuates strongly and exhibits shifts of more than π. To render single-shot information the interferogram is recorded with an inexpensive industrial 8-bit CCD with 2048 pixels in one line (UniLine-2048, Opti-Sens GmbH) that is triggered at the pulse repetition rate (1 kHz). In principle two detectors separated by $1/4$ of the interference period would be sufficient to record the signal [32], but such a setup depends critically on the alignment. To increase the intensity, a cylindrical lens ($f = 75$ mm) is used to image the interference pattern onto the CCD. The single-shot recordings reveal a high contrast interferogram with different fringe positions from pulse to pulse (see Fig. 3a). The contrast is limited by the difference in spectral intensity and dispersion, but mainly by the slightly different divergences of the beams.

The spatial interferogram is evaluated with a simple Fourier transformation and filtering technique [33]. The Fourier amplitude of a single-shot interferogram is depicted in Fig. 3b as a function of the "spatial" frequency. It peaks at zero, due to the spatial beam profile, and has two nontrivial peaks at $\pm f_0$ (see Fig. 3b), corresponding to the interference pattern with the fringe spacing $d_0 = 1/f_0$. The real and imaginary parts at the interference peak are shown in Fig. 3c for 600 consecutive pulses. The phase of each complex number yields the fringe position and therefore the CEP of the pulses with respect to a constant value.

The carrier-envelope phase fluctuations for the 600 consecutive pulses are shown in Fig. 4a. In this and several similar datasets, we found no regularity in the CEP with time and no correlation with the separately recorded pump intensity fluctuations. This is expected since the CEP of the pump laser system should be random from pulse to pulse and the continuum generation process preserves the CEP of the pump pulses [19]. A histogram for the 600 phases is shown in Fig. 4b and no significant deviation from a statistical distribution can be seen.

Although the NOPA pulses do not have an ultrabroad spectrum, they nevertheless preserve the phase properties of the white light continuum. The experiment therefore also determines the CEP fluctuations of the NOPA pulses.

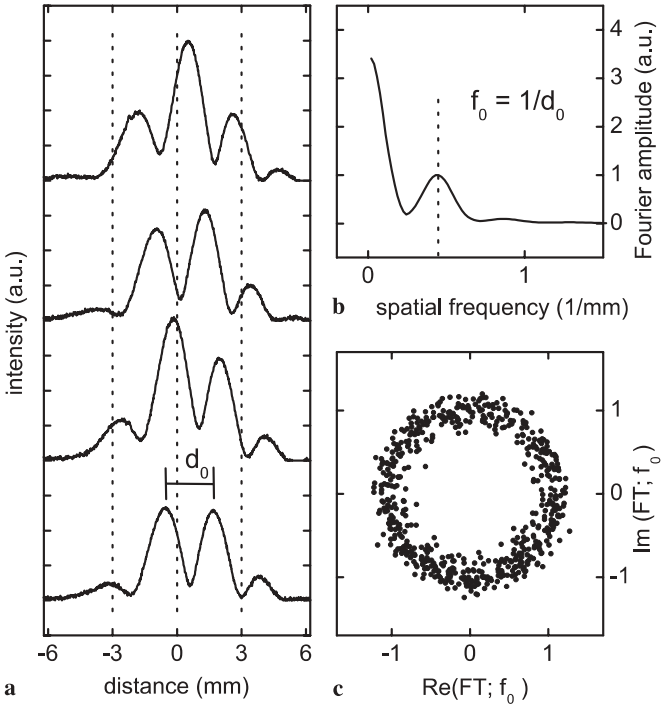

FIGURE 3 **a** Four examples of single shot spatial interferograms between the visible part of a white light continuum and the amplified infrared part that was subsequently frequency doubled. **b** Fourier transform of the interferogram. f_0 is the spatial frequency of the interference fringes. **c** Real and imaginary parts at the Fourier frequency f_0

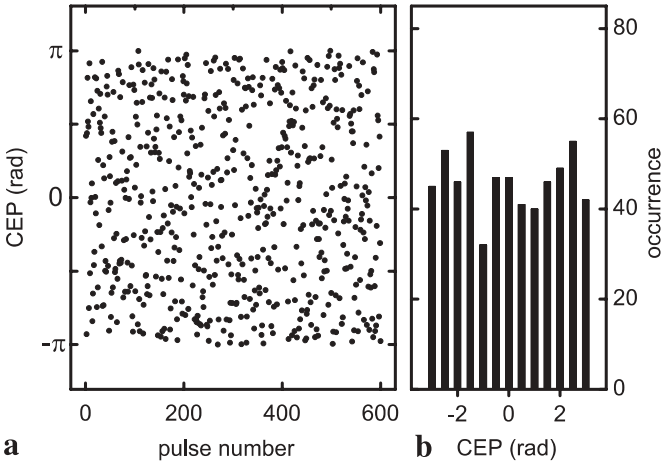

FIGURE 4 **a** Carrier-envelope phase fluctuations for 600 consecutive pulses. **b** Histogram of the 600 phase values

The 1100-nm pulses generated in the present experiment had pulse energies of about 1 μJ. Since the seed light intensity for a NOPA can be a small fraction of the typical white light output from the sapphire crystal, the generation of tunable pulses with a measured CEP variation is possible in the complete tuning range of the NOPA. Furthermore, only a small and selectable part of the IR and visible white light components are needed for the characterization, so one could operate it with spectral components not used for NOPA seeding.

The setup presented determines the CEP with respect to a constant offset value. However, the shift of the phase measured with our setup is the same as at the interaction point of an experiment. This allows the CEP shift to be recorded for each single laser pulse and the outcome of an experiment to be correlated with the CEP on a single-shot basis. Hence experiments sensitive to the CEP are possible without CEP stabilized light sources. If the absolute CEP has to be known a calibration at the experimental interaction point is ne-

cessary. This is in principle possible with highly nonlinear processes, but is a difficult experiment by itself. During beam propagation in dispersive media the CEP changes continuously because of the difference between the group and phase velocities. Therefore such a calibration is even necessary for light sources with a perfectly stabilized CEP.

The continuum generation process preserves the CEP of the pump source [19, 22]. A characterization of the CEP by the spatial interference setup presented reveals simultaneously the CEP shifts of the pump laser system. This information could be used to stabilize the CEP of the amplified Ti:sapphire pulses via a feedback loop analogous to schemes using spectral interferometry [10]. Another approach that avoids a complex feedback scheme might be to perform a fast electronic evaluation of the spatial interferogram and to use it as a signal for an electro-optical element (for example a Pockels cell), compensating for the CEP of a delayed replica of the same pulse.

4 Conclusion

In conclusion, we have demonstrated a direct and simple all optical approach to determine carrier-envelope phase fluctuations on a single-shot basis by spatially interfering different harmonics. This method eliminates the need for a spectrometer and a precise coaxial alignment. In the case of a low energy pulse, the low frequency components can be amplified before frequency doubling by optical parametric amplification. We have generated amplified tunable femtosecond pulses with a well characterized CEP shift. As expected the CEP of the NOPA pulses is statistical. The scheme presented is versatile with respect to the wavelength, since optical parametric amplification is available in a broad wavelength region to overcome low intensities that are not high enough for frequency doubling. The simplicity of the scheme opens up the route to CEP sensitive experiments on a single-shot basis without stabilized light sources.

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